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Projecting future climate change impacts on heat-related mortality in large urban areas in China

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ABSTRACT

Global climate change is anticipated to raise overall temperatures and has the potential to increase future mortality attributable to heat. Urban areas are particularly vulnerable to heat because of high concentrations of susceptible people. As the world's largest developing country, China has experienced noticeable changes in climate, partially evidenced by frequent occurrence of extreme heat in urban areas, which could expose millions of residents to summer heat stress that may result in increased health risk, including mortality. While there is a growing literature on future impacts of extreme temperatures on public health, projecting changes in future health outcomes associated with climate warming remains challenging and underexplored, particularly in developing countries. This is an exploratory study aimed at projecting future heat-related mortality risk in major urban areas in China. We focus on the 51 largest Chinese cities that include about one third of the total population in China, and project the potential changes in heat-related mortality based on 19 different global-scale climate models and three Representative Concentration Pathways (RCPs). City-specific risk estimates for high temperature and all-cause mortality were used to estimate annual heat-related mortality over two future twenty-year time periods. We estimated that for the 20-year period in Mid-21st century (2041–2060) relative to 1970–2000, incidence of excess heat-related mortality in the 51 cities to be approximately 37,800 (95% CI: 31,300–43,500), 31,700 (95% CI: 26,200–36,600) and 25,800 (95% CI: 21,300–29,800) deaths per year under RCP8.5, RCP4.5 and RCP2.6, respectively. Slowing climate change through the most stringent emission control scenario RCP2.6, relative to RCP8.5, was estimated to avoid 12,900 (95% CI: 10,800–14,800) deaths per year in the 51 cities in the 2050s, and 35,100 (95% CI: 29,200–40,100) deaths per year in the 2070s. The highest mortality risk is primarily in cities located in the North, East and Central regions of China. Population adaptation to heat is likely to reduce excess heat mortality, but the extent of adaptation is still unclear. Future heat mortality risk attributable to exposure to elevated warm season temperature is likely to be considerable in China's urban centers, with substantial geographic variations. Climate mitigation and heat risk management are needed to reduce such risk and produce substantial public health benefits.

1. Introduction

Climate change is anticipated to raise overall temperatures in the 21st century. Exposure to higher temperature in the warm season has been associated with both increased mortality and morbidity across the globe (Gasparrini et al., 2017; Guo et al., 2014; Huang et al., 2011; Zanobetti and Schwartz, 2008; Kinney et al., 2008;). Urban areas are particularly vulnerable to heat because of high concentrations of susceptible people as well as greater exposures associated with the urban heat island (Estrada et al., 2017; Li et al., 2015; Rosenzweig et al., 2010). As the world's largest developing country, China surpassed the U.S. and became the largest emitter of the primary greenhouse gas (GHG) carbon dioxide in 2007. Over the past 50 years, China has experienced noticeable changes in climate, with average air temperature rising by 0.5–0.8 °C (Kan, 2011). The nation is experiencing frequent occurrence of extreme heat in urban areas, which is likely to expose millions of residents to summer heat stress that could result in increased health risk, including mortality (Li et al., 2015). The trend of climate warming in China is projected to intensify in the future, which is likely to further increase the health risk associated with heat, particularly in large urban areas.

Future impacts of high temperatures on public health have been a

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topic of focused research in recent years (Gasparrini et al., 2017; Petkova et al., 2017, 2013; Weinberger et al., 2017; Schwartz et al., 2015; Mills et al., 2015; Wu et al., 2014; Voorhees et al., 2011; Knowlton et al., 2007; Also see a review by Sanderson et al. (2017)). Studies have consistently projected that a warmer future will lead to increase in future mortality on the order of thousands to tens of thousands of additional premature deaths per year in large countries such as the United States (US) (Sarofim et al., 2016), and over a hundred thousand per year globally (WHO, 2014). Although the decrease in cold season temperature is expected to result in decreases in deaths in winter months, recent studies have reported that increases in heat-related mortality could outweigh reductions in cold-related mortality, even in regions with colder climate (Gasparrini et al., 2017; Hajat et al., 2014; Li et al., 2013). Still, projecting changes in future health outcomes associated with climate warming remains challenging and subject to large uncertainties, and little is known about the future impacts of climate change in less developed countries, which are likely to be most vulnerable to climate change due to their reduced capacity to adapt and are also more vulnerable to climate-related damages (McCarthy, 2001).

The increase in future heat-related mortality is considered as one of the most likely impacts of climate change due to human activities. While climate-related health impacts are critical information in the economic assessments of climate change, to date they have been mostly overlooked by governments at all levels in energy and climate decision making. Therefore, projections of future heat mortality would provide valuable information to support climate policy decision making and heat-related risk management. Here we quantify excess heat-related mortality in the 51 largest urban areas in China in the 2050s and 2070s resulting from potential increases in future temperatures under three of the latest Representative Concentration Pathways emission scenarios developed for the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5, IPCC, 2014). The heat mortality projections are based on an integrated assessment framework that combines downscaled, very high resolution climate projections, city-specific temperature-mortality relationships, population projections and baseline mortality rates. We examine the future heat mortality impacts relative to the present situation, and also the differences of heat mortality between different future scenarios, which help to understand the potential benefits of reducing heat mortality risk through climate mitigation. We investigate sources of uncertainty including the temperature-mortality relationship, population projection, and human adaptation.

It is our goal to improve our understanding of possible impacts of elevated temperatures on public health in rapidly developing urban areas with high population density, where people may be especially vulnerable to global climate change, and also compare our findings with earlier projections in western developed countries. In addition to providing evidence of future heat-related mortality in the world's most populous developing county, this study improves earlier heat mortality projections by applying the latest RCP emission scenarios and the latest projections on China's population growth over the 21st Century, incorporating the newly developed city-specific temperature-mortality risk estimates, and using city-specific baseline mortality rates rather than national rates. Furthermore, given that population acclimatization and adaptation, such as improved human tolerance to heat and improvements in infrastructure and health care systems, has rarely been taken into account in existing projections, we use an “analogue city” approach to investigate the potential effects of adaptation on future temperature-related mortality estimates.

2. Materials and methods

2.1. Study areas and population

Based on the latest China census 2010 survey (National Bureau of Statistics of China, 2011), we selected 51 metropolitan areas in China to develop heat-related mortality projections for future climates (See Figs. 1 and 2 for the locations of the 51 cities). We included the four municipalities (Beijing, Tianjin, Shanghai and Chongqing),[1] the Hong Kong Special Administrative Region, and all province capital cities to ensure at least one city is selected in each province (generally in China, the capital is the major city in a province in terms of population and economic development). We also included non-capital cities that are among the top-30 cities by population. All together, these 51 cities encompass 0.458 billion, or roughly one third of the total 2010 Chinese population.

2.2. Climate models, emission scenarios, and future temperature projections

Using global climate model (GCM) outputs developed for IPCC AR5 (IPCC, 2014), we estimated future temperature changes in the mid (2050s) and late (2070s) 21st century in the 51 selected Chinese cities. We used downscaled, very high resolution climate data from the Coupled Model Intercomparison Project Phase 5 (CMIP5), which were developed for IPCC AR5. Data were obtained from WorldClim (http://worldclim.org/). The finest available spatial resolution of the data (30 arc-seconds, about 1 square kilometer) was used. Data for baseline conditions covered the time period of 1970–2000, and data for future conditions covered twenty-year time periods in the 2050s (2041–2060) and the 2070s (2061–2080). Future temperature projections for the 51 selected cities were developed by combining (averaging) the 30 arc-second down-scaled outputs from 19 GCMs from different modeling centers developed for IPCC AR5.[2]

IPCC AR5 uses four RCPs to describe different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use (IPCC, 2014). The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). We conduct heat-related mortality projections under three emission scenarios: RCP8.5, RCP4.5 and RCP2.6. RCP8.5 can be considered as the business as usual scenario - an emissions scenario of high population and high energy demand in absence of climate change policies over this century, yielding the RCP with the highest GHG emissions (Riahi et al., 2011). RCP4.5 is a stabilization scenario in which the total radiative forcing is stabilized shortly after 2100 (Thomson et al., 2011). RCP2.6 is representative of a scenario that leads to very low GHG concentration levels and aims to keep global warming likely below 2 °C above pre-industrial temperatures (Vuuren et al., 2011).

Annual heat-related mortality in the future were estimated using the modeled mean temperature of the warmest quarter (variable “BIO10” in the WorldClim dataset). Although different temperature metrics have been used to measure heat exposure, such as maximum, mean and minimum daily temperature, and apparent temperature (a metric that combines the effects of ambient temperature and relative humidity), earlier studies found no temperature measure was superior to the others (Barnett et al., 2010), and suggested that for the projection research of heat-related mortality, the temperature measure can be chosen based on practical concerns, such as using the measure that is commonly available from the climate models (Huang et al., 2011). Based on this, we selected the modeled mean temperature of the warmest quarter as the indicator of average human exposure to heat during the warm season, and linked it to heat-related mortality using temperature-mortality relationships reported in epidemiological studies. For each city, we averaged the model-simulated mean temperature of the warmest

[1] In China, municipalities are directly under the administration of central government. Despite their city-level areas and populations, a municipality has the same political, economic and jurisdictional rights as a province.

[2] These 19 GCMs include: ACCESS1-0, BCC-CSM1-1, CCSM4, CESM1-CAM5-1-FV2, CNRM-CM5, GFDL-CM3, GFDL-ESM2G, GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRI-CGCM3, and NorESM1-M.

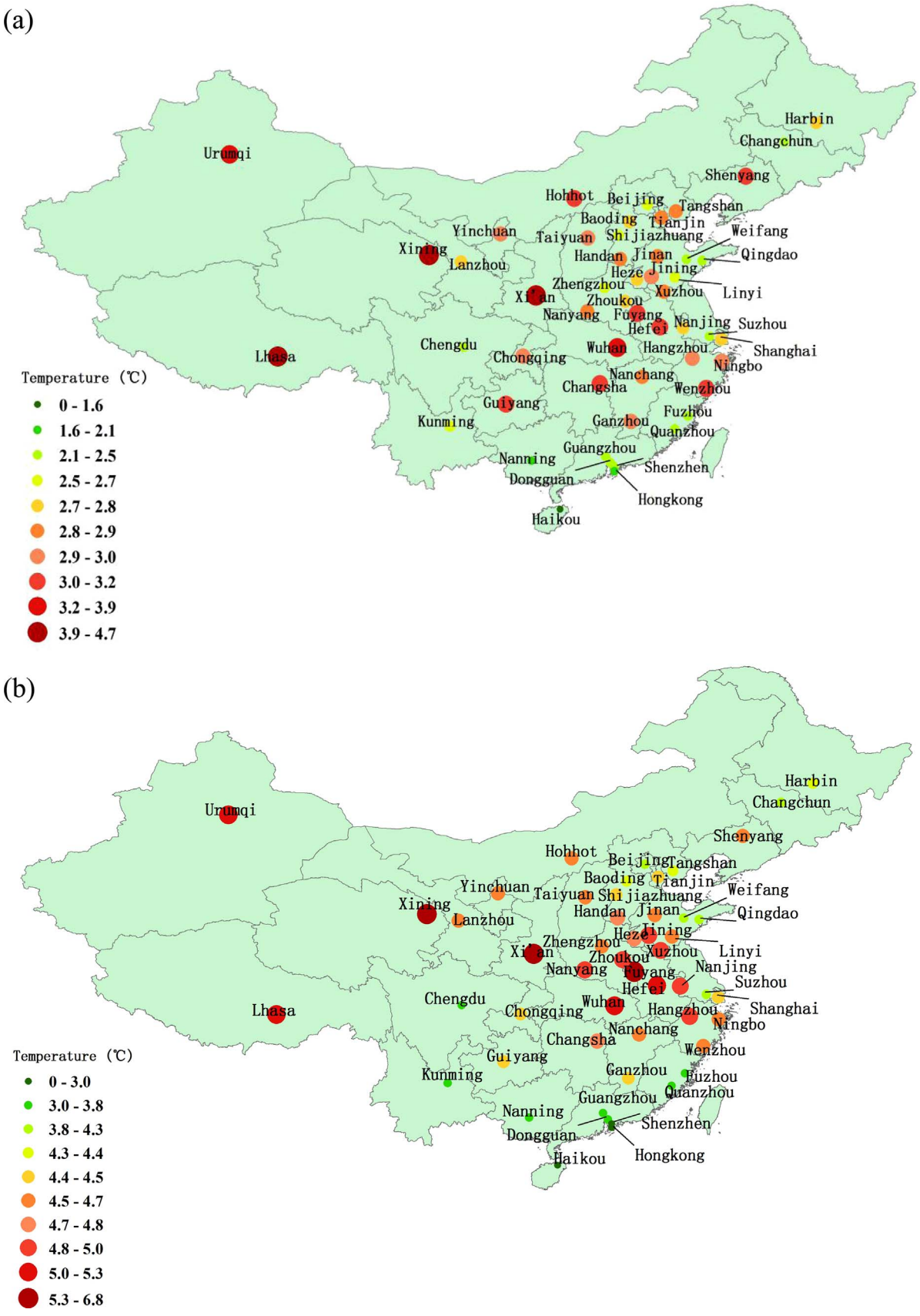

Fig. 1. Model-projected 2041–2060 (a) and 2061–2080 (b) mean temperature change (°C) relative to 1970–2000 for the warmest quarter under RCP8.5, calculated as (mean temperature for 2041–2060 or 2061–2080) – (mean temperature for 1970–2000).

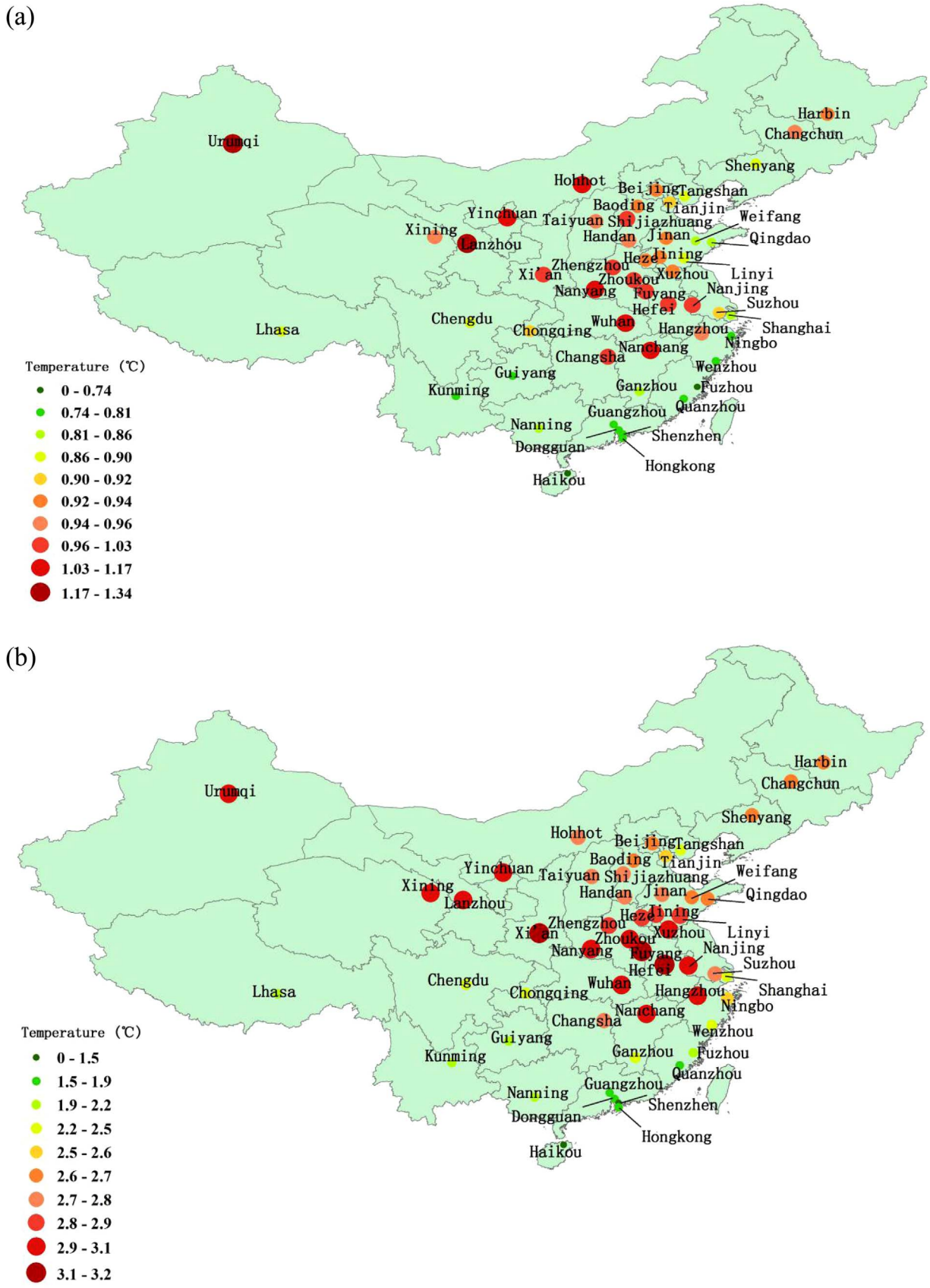

Fig. 2. Model-projected differences in mean temperature (°C) of the warmest quarter for 2041–2060 (a) and 2061–2080 (b) under high (RCP8.5) and low (RCP2.6) emission scenarios, calculated as temperature (RCP8.5) – temperature (RCP2.6).

Table 1
Historical temperature and future temperature projections in the 51 Chinese cities (average temperature in the warmest quarter over the model period across the 30 arc-second grid cells in a city boundary). The mean, median, minimum and maximum refer to statistics of all 51 cities.

Time period/Emission scenario		Average temperature in the warmest quarter (°C)			
		Mean	Median	Minimum	Maximum
1970–2000		24.4	25.7	9.7	28.6
2041–2060	RCP2.6	26.3	27.5	13.4	30.0
	RCP4.5	26.8	28.0	14.0	30.5
	RCP8.5	27.2	28.5	14.3	31.1
2061–2080	RCP2.6	26.3	27.6	13.3	30.0
	RCP4.5	27.3	28.5	14.4	31.1
	RCP8.5	28.9	29.9	15.7	33.0

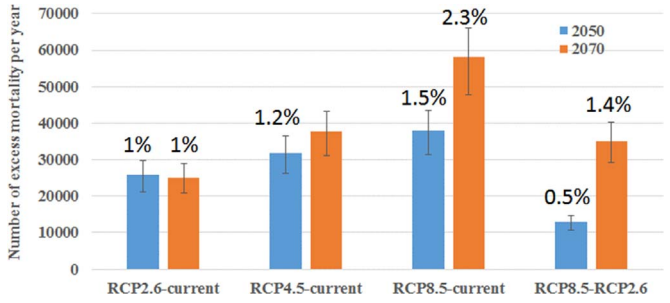

Fig. 3. Estimated increases in annual heat-related mortality for the 2050s and the 2070s under three future emissions scenarios (RCP2.6, RCP4.5 and RCP8.5) relative to the current condition (calculated based on the temperature difference between future and current climates in each city), and difference in estimated heat-related mortality between RCP8.5 and RCP2.6 (calculated based on the future temperature difference between RCP8.5 and RCP2.6 in each city). Percentages show the percentage change in overall mortality. Error bars are the 95% CI of estimates generated through Monte Carlo simulation by applying the uncertain ranges of the temperature-mortality relationships for each city (sample size of the simulation was set to 5000).

quarter in all 30 arc-second grid cells across the city for two future time periods: the 2050s (2041–2060) and 2070s (2061–2080), and the late 20th situation (the base period) (1970–2000). All climate data were analyzed using ArcGIS software (Version 10.2) by Esri.

2.3. Mortality risk projection

The excess heat-related mortality in the 51 cities in future time periods relative to the historical (base) time period was calculated using a damage function approach that has been used to relate changes in air pollution exposure to health impacts (Li et al., 2016a; Anenberg et al., 2010), but has also been used for quantifying heat impacts of climate change (Voorhees et al., 2011):

$$\Delta y = y_0 \times (1 - e^{-\beta \cdot \Delta x}) \times Pop \quad (1)$$

where Δy is the predicted change in mortality from increases in heat, y_0 is the baseline mortality rate, β is the temperature-mortality coefficient derived from epidemiological studies (unit increase in mortality per unit increase in temperature), Δx is the predicted change in exposure (heat exposure in this case, calculated as the exposure in a future time period relative to the baseline period), and *Pop* is the affected population.

Based on the variables in Eq. (1), we estimated the annual incidence of excess heat-related mortality in the 51 cities under future climates according to 19 different GCMs under three different RCPs in two future time periods: 2050s (2041–2060) and 2070s (2061–2080) relative to the late 20th century (1970–2000).

2.4. Temperature-mortality relationship

Future projections of heat mortality generally rely on historically developed temperature-mortality relationships (Schwartz et al., 2015). The temperature-mortality association is a key parameter in projecting future heat-related mortality. Studies in different continents have reported that temperature-mortality relationships vary in a nonlinear U-, V- or J-shaped fashion, with both winter cold and summer heat spells being associated with increased deaths above a threshold temperature (Kinney et al., 2008; Huang et al., 2011; Gasparrini et al., 2015a, b; Honda et al., 2014). The observed temperature-mortality associations and threshold temperatures vary by climate and socio-demographic factors (such as age, race and poverty) (Sarofim et al., 2016). Most of the studies on high ambient temperature and mortality rely on the time-series or case-crossover study designs, with the latter gaining widespread popularity for studying air pollution and temperature in recent years since this design controls factors (e.g. genetics, health behaviors, and seasonal effects) that would otherwise be difficult to control by matching case and controls days in a relatively small time window (Basu, 2009; Guo et al., 2011). Regardless of the study designs, the time-series and case-crossover studies yield similar results (Basu, 2009).

There is a growing literature on epidemiological studies of temperature-mortality relationships in China (e.g. Zhang et al., 2017; Zhang et al., 2016; Ma et al., 2015; Gao et al., 2015; Li et al., 2012; Guo et al., 2011; Liu et al., 2011; among others), which provides a solid scientific basis for future projections of heat mortality in the country. In order to derive best available city-specific temperature-mortality risk estimates in our study areas, we conducted a comprehensive review of existing literature of elevated ambient temperature and mortality in China. A literature search was conducted using the electronic databases PubMed (National Library of Medicine 2010), Web of Science, ScienceDirect, ProQuest, and Scopus. The search was limited to journal articles published in English. The key words used were temperature, heat, mortality, death and China. We found city-specific temperature-mortality risk estimates for 17 of the 51 cities and applied these risk estimates to the cities in our projection (Table A1). For the remaining 34 cities where their city-specific estimates are not available, we assigned the risk estimate from a nearby city that has its heat risk estimate, and is within a short distance (around 100 km or shorter) and also has similar climate characteristics to the target city. In the case that there is no nearby city with a risk estimate, regional estimates from Ma et al. (2015) were used. The effect estimates from each study were converted into the temperature-mortality coefficient β in Eq. (1) (Table A1).

We found that the temperature-mortality risk estimates for Chinese cities are generally higher than those reported in western developed countries such as the US (Anderson and Bell, 2009, for instance). Higher β values indicate that population in China may have greater vulnerability to elevated temperature in the warm season, which may be explained by the lesser adaptive capacity typically in developing countries compared to developed countries, such as access to air conditioning, health care and heat illness prevention programs. Without further adaptation strategies, it is likely that heat-related mortality in China will increase significantly in the future due to global climate change.

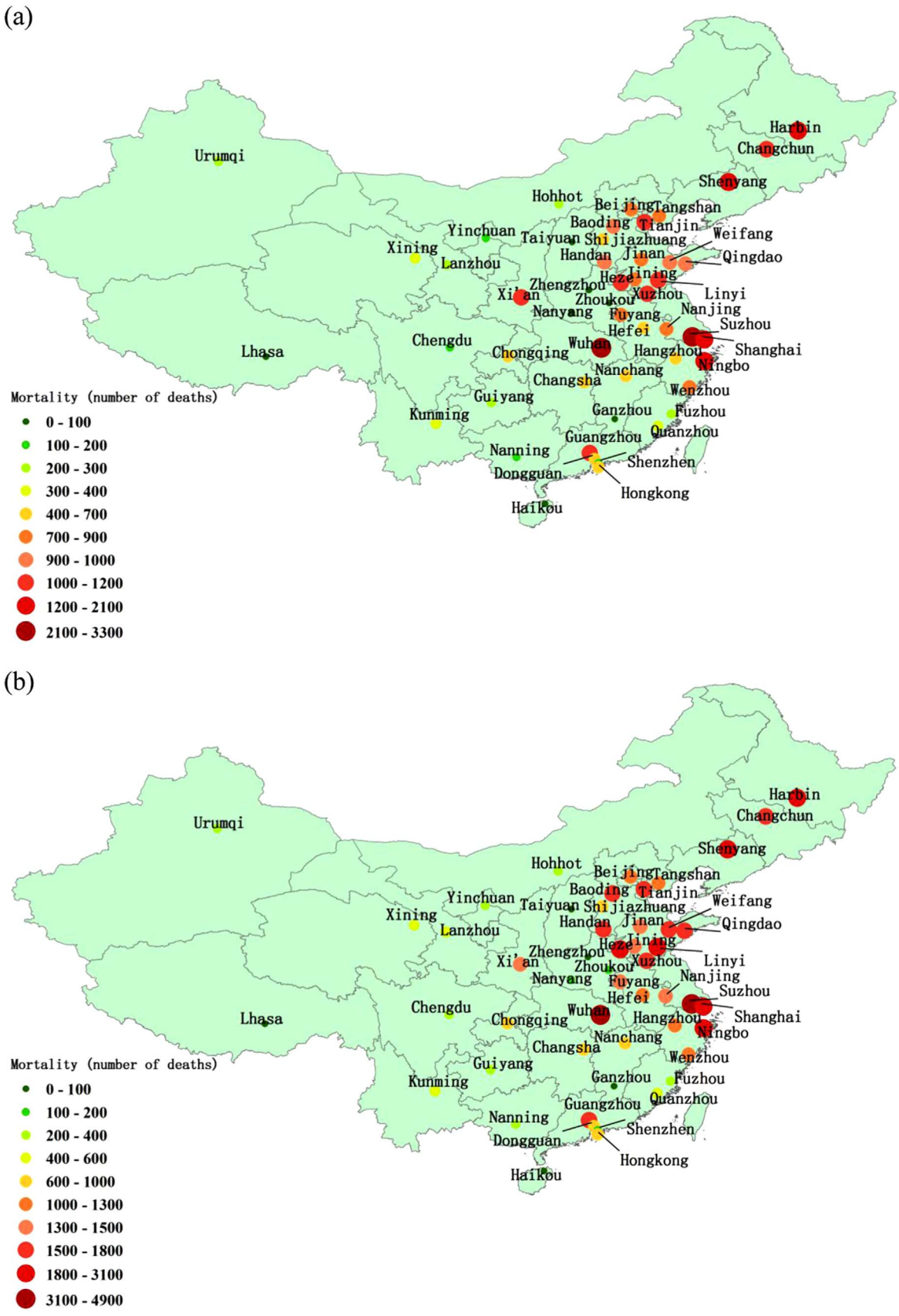

Fig. 4. Estimated annual incidence of excess heat-related mortality for 2041–2060 (a) and 2061–2080 (b) relative to 1970–2000 in the 51 cities under emission scenario RCP8.5.

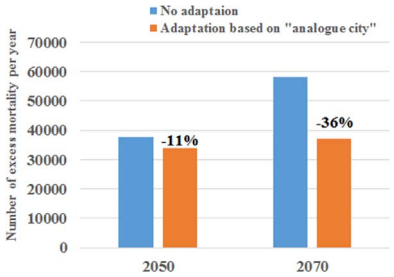

Fig. 5. Comparing excess heat-related mortality estimates under RCP8.5 with and without population adaptation in 2050 and 2070 (percentage values indicate the changes when adaption is assumed relative to the "no adaptation" scenario).

2.5. Population projections and baseline mortality rates

We relied on the China census 2010 survey (National Bureau of Statistics of China, 2011) and the Chinese population growth rates in future decades from the latest 2015 Revision of World Population Prospects (RWPP, United Nations, 2015) to project population growth in the 51 cities in the 2050s and the 2070s. 2015 RWPP is the twenty-fourth round of official United Nations population estimates and projections that have been prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. It gives population growth rates in five year increments until the end of the 21st Century. Baseline mortality rates of the 51 cities for six consecutive years (2009–2014) were obtained from China's national and local health statistics publications, including the China Statistical Yearbook at the national and local levels. We then averaged the mortality rates of the six years for each city and applied the six-year average to our two projection periods, 2050s and 2070s.

3. Results

3.1. Future temperature projections

We generated average temperature in the warmest quarter for the base period (1970–2000) and two 20-year periods in the future (2041–2060 and 2061–2080) for the 51 cities (Table 1). The climate model results indicate significant warming in these cities across China in the mid- and late-21st century relative to the based period under all three RCP scenarios. The mean of the warmest quarter temperature for the 51 cities shifted from 24.4 °C in years 1970–2000 to 26.3 °C (RCP2.6), 26.8 °C (RCP4.5), and 27.2 °C (RCP8.5) in 2041–2060. Under RCP4.5 and RCP8.5, the mean temperature will further increase to 27.3 °C and 28.9 °C, respectively, in 2061–2080. The range of the average temperature across the 51 cities shifted from between 9.7 and 28.6 °C to between 14.3 and 31.1 °C in the 2050s, and to between 15.7 and 33 °C in the 2070s, under RCP8.5. RCP2.6 is predicted to stabilize future temperatures between 2050s and 2070s. Fig. 1 shows the model-projected average temperature increases in the warmest quarter over 2041–2060 and 2061–2080 relative to 1970–2000 under the highest emission scenario RCP8.5. Under RCP8.5, average temperature in the warmest quarter is predicted to be higher in the 2050s by 1.6–4.7 °C in the 51 Chinese cities (Fig. 1a), and to be higher by 3.0–6.8 °C in the 2070s (Fig. 1b), with the most pronounced differences occurring in Central and Western China and some areas in the Yangtze River Delta. Refer to Fig. A1 and A2 in the Appendix for temperature changes under RCP4.5 and RCP2.6, respectively. Fig. 2 shows the difference in projected average temperature in the warmest quarter over 2041–2060 and 2061–2080 between the highest emission scenario (RCP8.5) and the lowest emission scenario (RCP2.6). Fig. 2 indicates that projected future temperatures will be 0.7–1.3 °C higher under RCP8.5 relative to RCP2.6 in the 2050s, and 1.5–3.2 °C higher in the 2070s, with the most pronounced differences occurring in the North and Central regions.

3.2. Projected changes in heat-related mortality

Fig. 3 shows the estimated increases in total heat-related all-cause mortality in the 51 cities in the 2050s and the 2070s based on model-simulated temperature under RCP8.5, RCP4.5 and RCP2.6 scenarios relative to 1970–2000. Fig. 3 also includes differences in mortality estimates under the highest emission scenario RCP8.5 relative to the lowest emission scenario RCP2.6. Using city-specific risk estimates for the 51 largest urban areas in China, we estimated that for the 20-year period in the mid-21st century (2041–2060) relative to the base period, annual incidence of excess heat-related mortality in the 51 cities to be approximately 37,800 (95% CI: 31,300–43,500), 31,700 (95% CI: 26,200–36,600) and 25,800 (95% CI: 21,300–29,800) deaths per year under RCP8.5, RCP4.5 and RCP2.6, respectively. For the late-century study period (2061–2080), the annual excess heat mortality estimates were 58,100 (95% CI: 47,900–66,200), 37,700 (95% CI: 31,200–43,300) and 25,100 (95% CI: 20,800–29,000) under RCP8.5, RCP4.5 and RCP2.6, respectively. These results are considered as additional heat-related deaths per year in the 2050s and the 2070s as a result of global climate change. Slowing climate change through the most stringent emission control scenario RCP2.6, relative to RCP8.5 was estimated to avoid 12,900 (95% CI: 10,800–14,800) and 35,100 (95% CI: 29,200–40,100) deaths per year in the 51 cities in the 2050s and 2070s, respectively.

Fig. 4 shows the annual heat mortality estimates in the 51 cities in the two future time periods under RCP8.5. Fig. 4 indicates substantial geographic variations in heat mortality across the 51 cities. The highest mortality mostly occur in the North, East and Central China. The top-five ranked cities with the largest annual heat mortality are Wuhan, Suzhou, Ningbo, Shenyang and Harbin. Refer to Fig. A3 and A4 for heat-mortality estimates in the 51 cities under RCP4.5 and RCP2.6, respectively, and Fig. A5 for differences in mortality estimates under the highest emission scenario RCP8.5 relative to the lowest emission scenario RCP2.6 in each city.

Table 2
Comparing future heat-related mortality estimates by this study with two similar studies in the Unites States.

Reference	Study population	Projection period	Emission scenario	Climate models	Annual temperature-attributable premature deaths
Voorhees et al. (2011)	United States, roughly 400 million	May-Sept. 2048–2052	A1B	GISS-I/MM5	21,000
Schwartz et al. (2015)	209 US cities (roughly 189 million, or 1/2 of the US population)	April-Sept. 2030, 2050, 2100	RCP6.0	GFDL-CM3 and MIROC5	6950–11646 in 2030; 9462–15229 in 2050; 19509–27312 in 2100
Present study	51 large Chinese cities, roughly 460 million	Warmest quarter 2041–2060 Warmest quarter 2061–2080	RCP8.5, RCP4.5 and RCP2.6	19 GCMs	RCP8.5: 37,800; RCP4.5: 31,700; RCP2.6: 25,800 RCP8.5: 58,100; RCP4.5: 37,700; RCP2.6: 25,100

4. Discussion

Projected changes in future heat-related mortality associated with climate change can be difficult to quantify. Projections can be affected by the relationships between heat exposure and deaths; future changes in baseline mortality rates, human tolerance and adaptive capacity; population growth and the changing proportions of vulnerable populations, such as the elderly; and climate projections (Sarofim et al., 2016). This study applies model outputs from 19 state-of-the-art global-scale GCMs from different modeling centers to reduce uncertainty in climate projections by a single model, and two 20-year periods of climate realization to reduce uncertainty in year-to-year variation. We use Monte Carlo simulation to evaluate the uncertainty associated with temperature-mortality relationships by applying the uncertain ranges and PDFs of these relationships obtained from epidemiological studies. We test the sensitivity of heat mortality projections to population growth by evaluating a scenario without site-specific population changes. Finally, we investigate the uncertainty in future population adaptation by using an "analogue city" approach given in Knowlton et al. (2007). This approach uses temperature-mortality response functions from analogue cities whose present climate best approximates the projected future climate of a target city to reflect potential adaptation over time in the target city.

4.1. Sensitivity analysis of population projection

We relied on United Nations' 2015 RWPP to project future population in this study. RWPP predicts that China's population will steadily stabilize until the 2030 s, and then start to decline. Based on that projection, our estimates of future population in the 2050s in the 51 cities are slightly (approximately 3%) larger than the 2010 baseline population, and the population size in the 2070s is approximately 2% smaller compared to the baseline. An earlier study on projecting future heat-related mortality in China assumed populations remain unchanged in the 21st century (Li et al., 2015). Here we also tested the sensitivity of heat mortality projections to population growth by holding future population in the 51 cities unchanged, which resulted in a slight decrease (approximately 0.5%) in the 2050s heat mortality estimates and a slight increase (approximately 1.9%) in the 2070s estimates under all three RCP scenarios. Our results indicate that population growth as a whole will not play a significant role in future excess heat-related mortality due to China's stabilized population in the foreseeable future.

4.2. Analysis of population adaptation

Another significant uncertainty associated with future heat-related mortality projections is adaptation. Communities may adapt to extreme heat through increased use of air conditioning, modified behavior patterns, as well as improved building designs and urban planning (Kinney et al., 2008; Huang et al., 2011). Earlier studies suggest that air conditioning is likely to be an important adaptive mechanism (Kinney et al., 2008). Also, studies in the US reported that populations have become less sensitive to heat over time, owing to factors including increased access and use of air conditioning in homes and businesses, and increased access to public health programs and healthcare (Sarofim et al., 2016; Bobb et al., 2014; Petkova et al., 2014). Future change in adaptive capacity is likely to reduce future increases in heat-related mortality (Hondula et al., 2015), whereas the ability to adapt may be limited by socio-economic conditions such as the costs prices of air conditioning and electricity (Kinney et al., 2008).

The current lifestyle of residents in China still heavily relies on natural ventilation with the tendency keep windows open during a significant amount of time in a year, including summers. The costs of using air conditioning are often an issue of concern for low-income populations. In addition, during extreme weather, there is a much higher risk of power outages in large urban areas. Given these factors, it is not very likely that air conditioning use in China will increase dramatically over the next several decades, particularly in residential homes and among the older generations. Here we investigate the impacts of adaptation on heat mortality using the "analogue city" approach given in Knowlton et al. (2007). This approach uses temperature-mortality response functions from analogue cities whose present climate best approximates the projected future climate of a target city to reflect potential adaptation over time in the target city. We applied this approach to test the heat mortality estimates under RCP8.5. Our results show that the "analogue city" adaptation assumption resulted in a decrease of 11% and 36% in projected heat mortality in the 2050s and the 2070s, respectively (Fig. 5). These estimates suggest that the decrease in future heat mortality as a result of population adaptation is likely to be nontrivial, which is consistent with findings from some earlier studies (Petkova et al., 2017; Bobb et al., 2014).

To our best knowledge, this is the first attempt to quantify future climate change impacts on heat-related mortality for a large fraction of China. While similar studies to project future heat-related mortality at the national level have been conducted in western developed countries such as the U.S., the large number of variables that determine heat-mortality estimates and their inherent uncertainties makes cross-study comparisons difficult (Voorhees et al., 2011). Projected changes in future mortality associated with elevated temperatures can depend on many factors such as choices of climate models, emission scenarios, temperature-mortality functions, study time periods, and future population projections. Since our study population is similar in size to the entire U.S. population, we compare our findings with two recent US projections of national heat-related mortality (Table 2), one covered the entire US population (Voorhees et al., 2011) and the other covered 209 US cities, or roughly half of the US population (Schwartz et al., 2015). Given that we only estimated heat-attributable premature deaths for three months (the warmest quarter), whereas the US studies estimated deaths for more months (May to September in the Voorhees study and April to September in the Schwartz study), our estimates of heat mortality for the mid-century period under similar emission scenarios were at least 50% greater than the U.S. estimates. The difference can be partially explained by the greater temperature-mortality associations reported by studies in China compared to those reported in the U.S. studies. On average, the city-specific temperature-mortality association used in this study is a 2.2% (range: 0.17–7.6%) increase in mortality per 1 °C increase in mean temperature, whereas the U.S. studies reported a value ranging from roughly a 0.3–0.5% increase in mortality per 1 °C, indicating the Chinese population may be more vulnerable to elevated temperature in the warm season. Other factors, such as the differences in climate models, emission scenarios as well as baseline mortality rates, may also have contributed to the differences in heat mortality estimates between the two countries.

5. Conclusions and future work

Using future temperature projections from 10 global climate models, location-specific estimates of temperature-mortality associations, and city-level population projections and baseline mortality rates, we estimated future excess heat-related mortality in 51 major cities in China under three RCP emission scenarios in mid- and late-21st Century. We estimated that for the 20-year period in Mid-21st century (2041–2060) relative to 1970–2000, incidence of excess heat-related mortality in the 51 cities to be approximately 37,800 (95% CI:

31,300–43,500), 31,700 (95% CI: 26,200–36,600) and 25,800 (95% CI: 21,300–29,800) deaths per year under RCP8.5, RCP4.5 and RCP2.6, respectively. In the late century (2061–2080), the annual cases of excess deaths will stabilize under the lowest emission scenario RCP2.6, but will further increase under the scenarios RCP4.5 and RCP8.5. Overall, our findings suggest that future heat mortality risk attributable to exposure to elevated warm season temperature is likely to be considerable in China's urban centers. Consequently, heat risk management will be needed to reduce such risk and produce substantial public health benefits in China. Our results also indicate that slowing climate change through the most stringent emission control scenario RCP2.6, relative to RCP8.5, would avoid 12,900 (95% CI: 10,800–14,800) deaths per year in the 51 cities in the 2050s, and 35,100 (95% CI: 29,200–40,100) deaths per year in the 2070s, yielding considerable public health benefits of climate mitigation.

Our estimates of excess heat-related mortality have some uncertainties and limitations. First, although we found that population adaptation to heat may moderately decrease excess heat mortality resulting from elevated temperatures based on the “analogue city” assumption, the actual adaptive capacity among the urban population in China is still uncertain due to the lifestyle of urban residents and current uncertainty in the extent of future population adaptation to climate change (WHO, 2014). We also found that heat mortality estimates are insensitive to different assumptions on future population growth, due to the stabilization of the Chinese population over this century. However, in a large-scale projection like this, the available data did not allow us to take into account population age structure changes, which is occurring rapidly in China's population with the proportion of older adults increasing significantly due to the country's most stringent population control policy. Studies have suggested that not considering population aging may significantly underestimate heat mortality risk (Lee and Kim, 2016; Li et al., 2016b). Future work should apply age-specific temperature-mortality relationships and mortality rates in heat mortality projections. Another limitation of this study is that daily temperature projections with high spatial resolution, downscaled from the outputs of GCMs, are not available across a large geographical scale in China. Thus we relied on published exposure-response relationships between daily temperature and mortality and the projections of mean temperature in the warmest quarter to estimate excess mortality in the future, assuming a linear relationship between temperature and health effects. Due to the quadratic or exponential increases in risk as warm temperatures become more extreme, which are commonly reported in epidemiologic literature (Gasparrini et al., 2017; Kinney et al., 2008), it is likely that our approach underestimates the mortality resulting from extreme heat. Finally, we relied on published city-specific temperature-mortality risk estimates to project future excess mortality, but only able to locate these risk estimates for 17 of the 51 cities from the current epidemiologic literature. As a result, we substituted those missing temperature-mortality relationships using estimates from a nearby city with a similar climate, or using regional risk estimates. As this process introduced uncertainties in heat mortality projections, future work should incorporate more city-specific risk estimates when they become available.

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Appendix A:

See Table A1

Table A1
City-specific temperature-mortality risk estimates used in this study.

Reference	City	Study Period	Beta Value for All-Cause Mortality (per 1 °C Increase) (95% CI)
Ma et al. (2014)	Beijing	2007–2008	0.025 (−0.005, 0.055)
Wu et al. (2013)	Changsha	2006–2009	0.02 (0.003, 0.037)
Wu et al. (2013)	Guangzhou	2006–2010	0.029 (0.02, 0.039)
Ma et al. (2014)	Hangzhou	2002–2004	0.01 (−0.03, 0.06)
Chan et al. (2012)	Hong Kong	1998–2006	0.018 (0.007, 0.03)
Wu et al. (2013)	Kunming	2006–2009	0.017 (0.004, 0.03)
Ma et al. (2014)	Lanzhou	2004–2008	0.005 (−0.030, 0.035)
Bai et al. (2014)	Lasha	2008–2012	0.015 (−0.022, 0.061)
Ma et al. (2014)	Nanjing	2001–2004	0.01 (−0.005, 0.025)
Zhang et al. (2014)	Shanghai	2004–2008	0.018 (0.0008, 0.026)
Ma et al. (2014)	Shenyang	2005–2008	0.03 (0.01, 0.06)
Wang et al. (2014)	Suzhou	2005–2008	0.065 (0.047, 0.085)
Ma et al. (2014)	Taiyuan	2006–2008	0.075 (0.055, 0.11)
Guo et al. (2011)	Tianjin	2005–2007	0.02 (0.007, 0.034)
Zhang et al. (2016)	Wuhan	2003–2010	0.076 (0.045, 0.10)
Ma et al. (2014)	Wulumuqi	2003–2005	0.045 (−0.02,0.092)
Ma et al. (2014)	Xi’an	2001–2004	0.028 (0.001, 0.057)

See Figs. A1–A5

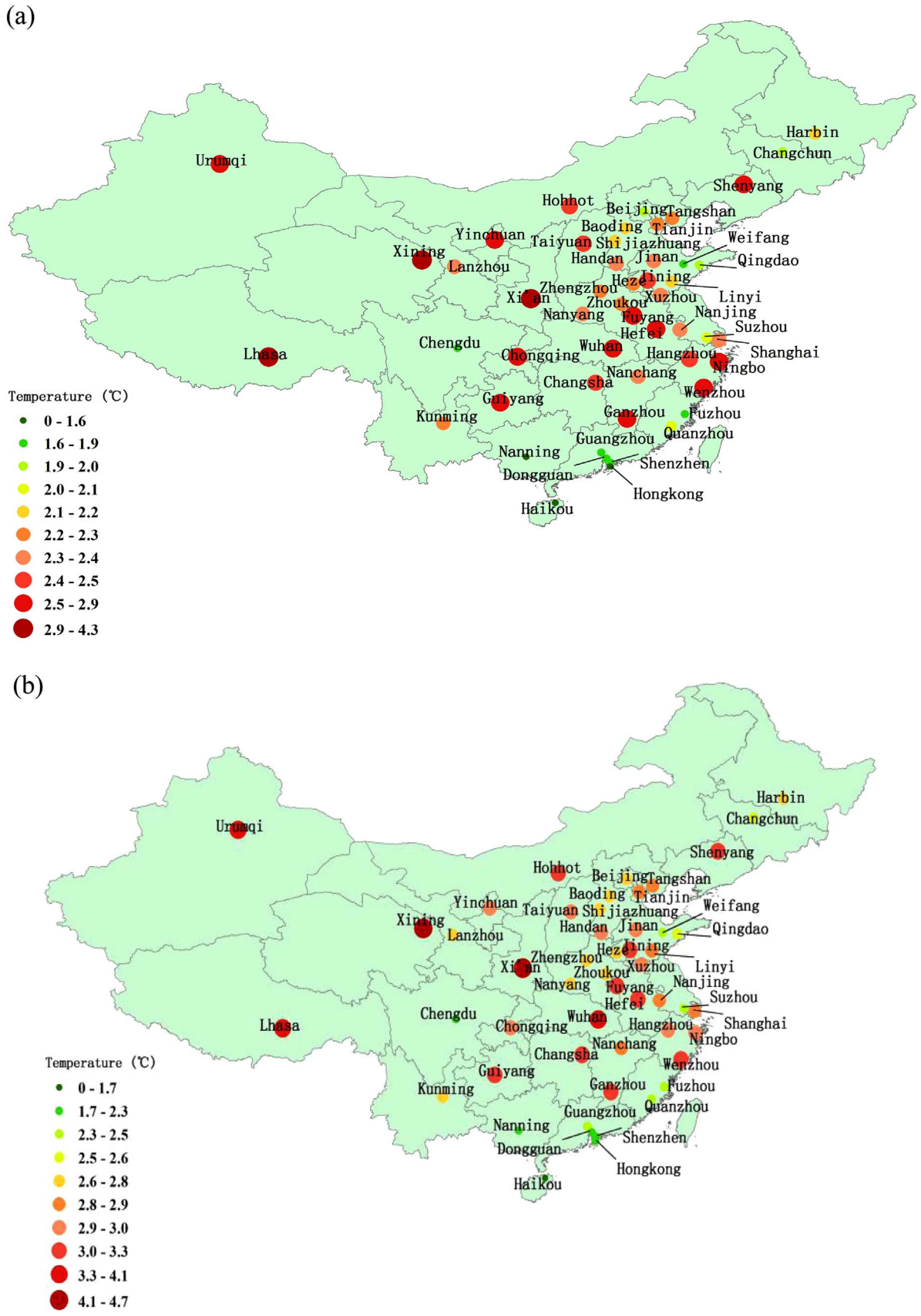

Fig. A1. Model-projected 2041–2060 (a) and 2061–2080 (b) mean temperature change (°C) relative to 1970–2000 for the warmest quarter under RCP4.5, calculated as (mean temperature for 2041–2060 or 2061–2080) – (mean temperature for 1970–2000).

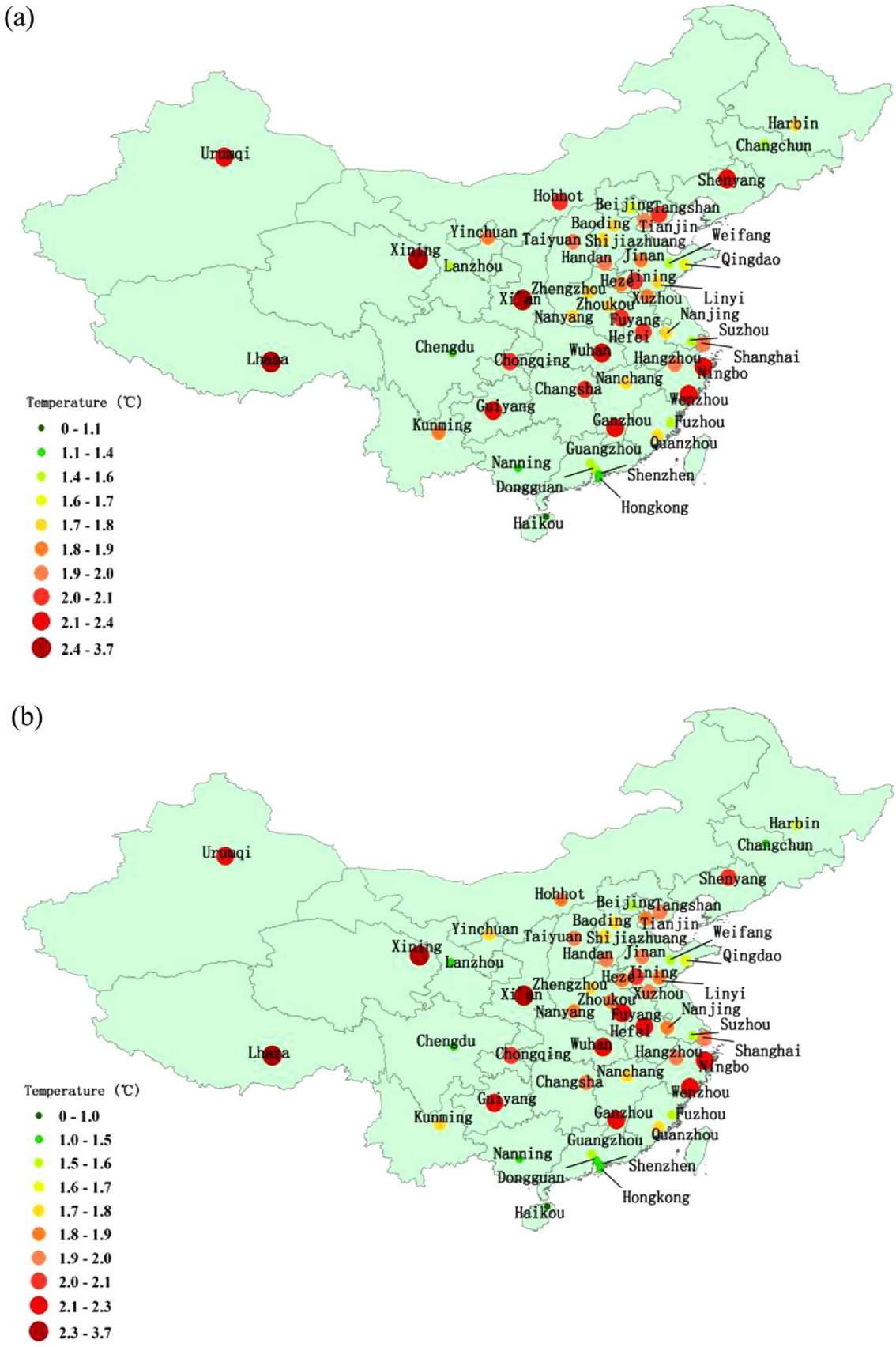

Fig. A2. Model-projected 2041–2060 (a) and 2061–2080 (b) mean temperature change (°C) relative to 1970–2000 for the warmest quarter under RCP2.6, calculated as (mean temperature for 2041–2060 or 2061–2080) – (mean temperature for 1970–2000).

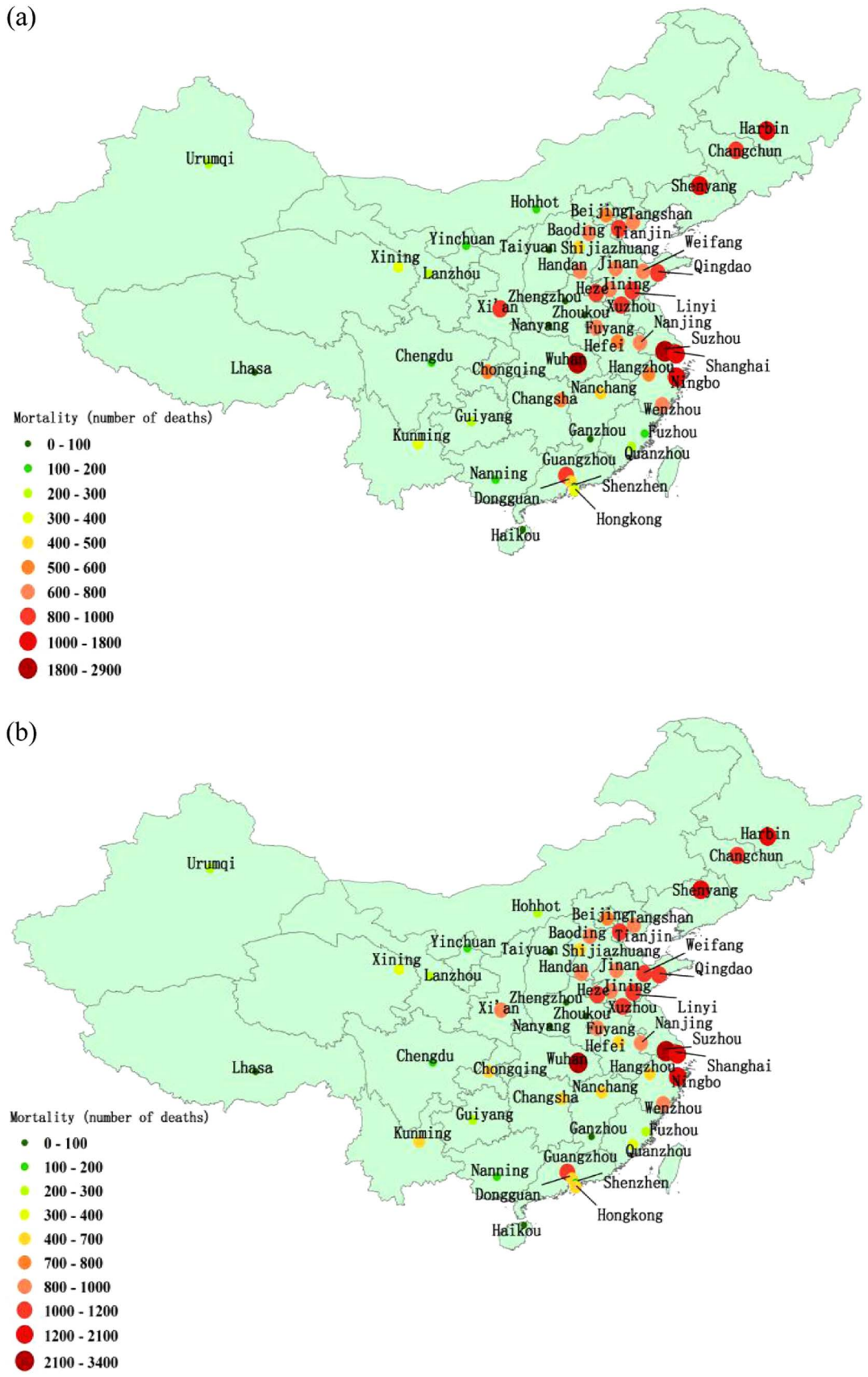

Fig. A3. Estimated annual incidence of excess heat-related mortality for 2041–2060 (a) and 2061–2080 (b) relative to 1970–2000 in the 51 cities under emission scenario RCP4.5.

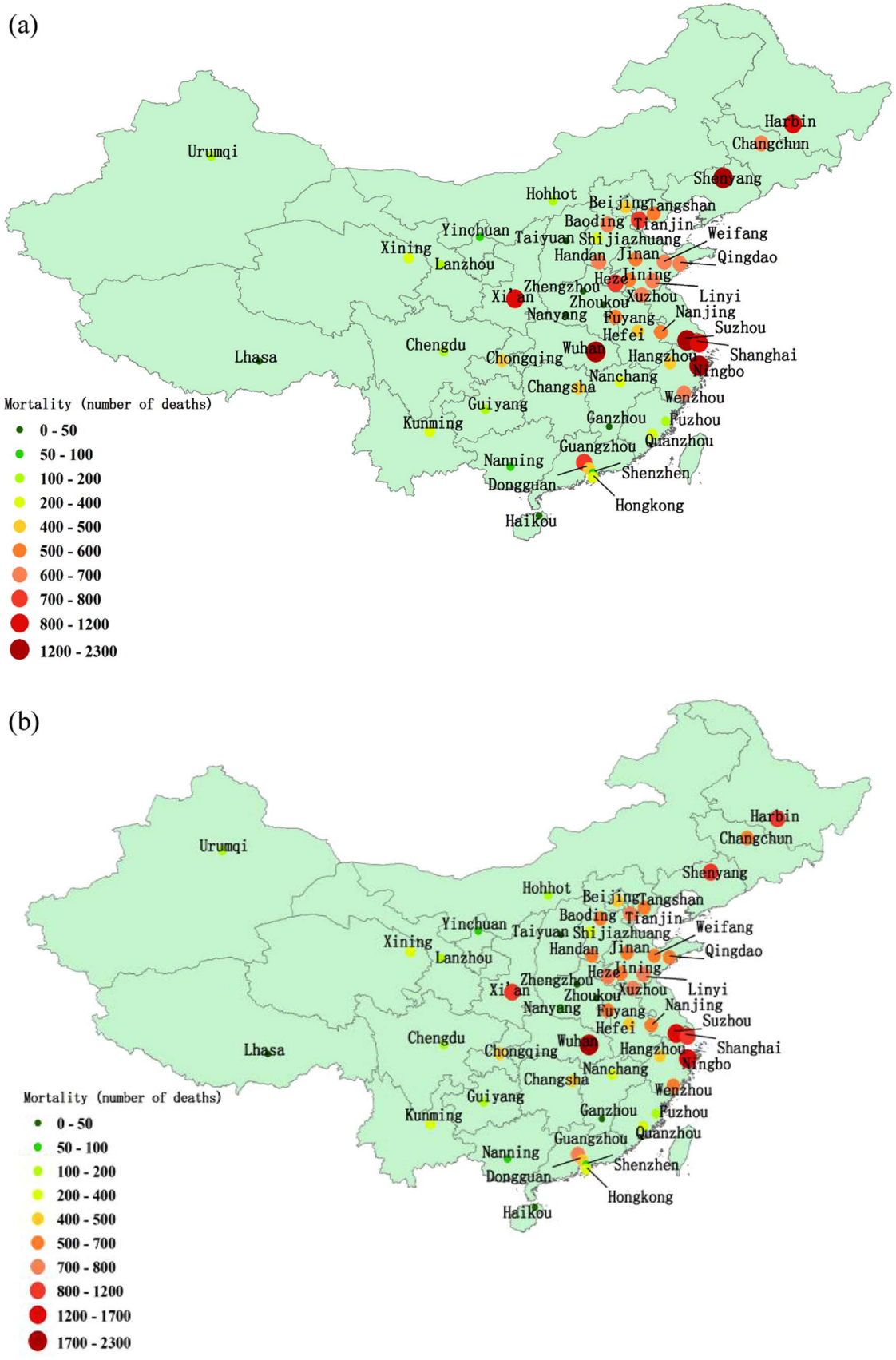

Fig. A4. Estimated annual incidence of excess heat-related mortality for 2041–2060 (a) and 2061–2080 (b) relative to 1970–2000 in the 51 cities under emission scenario RCP2.6.

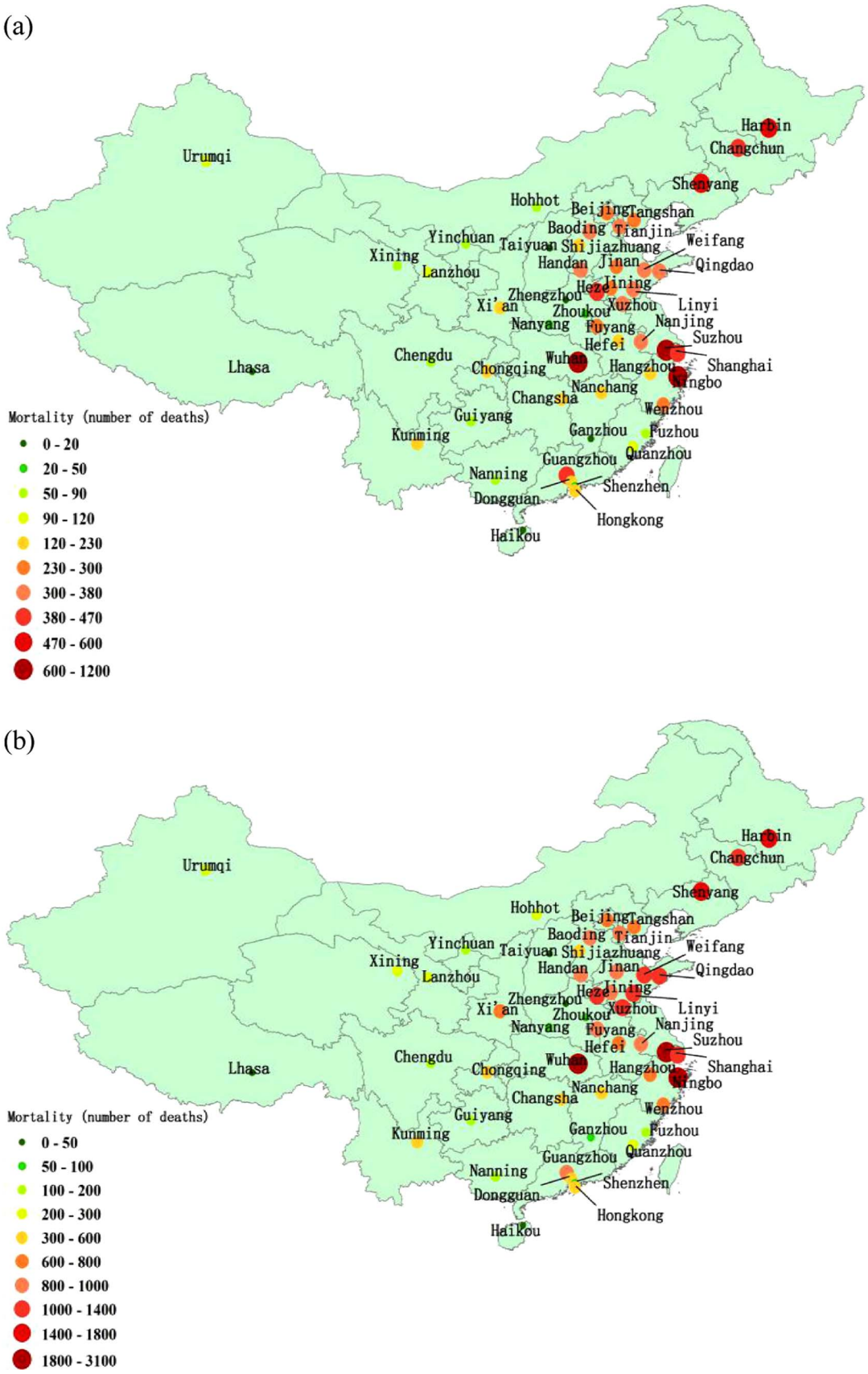

Fig. A5. Differences in mortality estimates under RCP8.5 relative to RCP2.6 for 2041–2060 (a) and 2061–2080 (b) in the 51 cities.

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